HYBRID SIMULATION OF THE SUPERHEATERS OF THE 110 MW BOILER UNIT OF PANKI THERMAL POWER STATION

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CERTIFICATE

This is to certify that this work entitled 'HYBRID SIMULATION OF THE SUPERHEATERS OF THE 110 MW BOILER UNIT OF PANKI THERMAL POWER STATION' by Shri K. Balagopal has been carried out under our supervision and has not been submitted elsewhere for the award of a degree.

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SYNOPSIS

HYBRID SIMULATION OF THE SUPERHEATERS OF THE 110 MW BOILER UNIT OF PANKI THERMAL POWER STATION

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By

K. Balagopal

The non-linear mathematical model of the superheaters of 110 MW Panki Thermal Power Station is simulated on hybrid computer system. The responses are compared with digital simulation responses. It is seen that the maximum error between the results is of the order of 1 percent. A linearized form for the non-linear model has also been obtained and simulated. The results compare well with the non-linear model. The advantage of using hybrid simulation over digital computation can be had from the fact that the computation time required in the hybrid mode for the non-linear model was only 5 minutes (at 1/6 slowed down scale) whereas a 4th order Runge-Kutta digital simulation on the same computer (IBM 1800) in digital mode took two hours.

CHAPTER 1

INTRODUCTION

1.1 HYBRID COMPUTERS - AN INTRODUCTION

In the pursuit of accuracy, speed and economy in the simulation of mathematical models of physical systems, analysts are continuously searching for more and more sophisticated mathematical techniques and computer systems. When the complexity of the mathematical model increases, their simulation on pure analog or pure digital computers are frequently cumbersome. The main reason for this is that some of the operations in mathematical model are inherently best handled either on the digital or on the analog computer.

The chief distinction between analog and digital computers lies in the manner in which the dependent variables are handled within the computer. In analog machines, dependent variables (though not necessarily the independent variables) appear everywhere in continuous form and may be recorded with as many significant figures as the quality of the circuit component permits. In digital computers, all variables appear in discrete form, and the accuracy of the data which are manipulated and recorded as the output of the digital computation depends on the number of digits carried throughout the solution and is directly related to the capacity or size of the memory registers.

Some advantages of analog computers are,

(i) the dependent variables are in continuous form,

(ii) the operation is parallel, with all computational, elements operating simultaneously and hence high-speed or real-time operation, (speed depends upon the bandwidth characteristics of the elements, not by the complexity of the problem),

Some of the draw-backs of analog computers are,

(i) lesser accuracy, accuracy depends upon the quality of the computer components and rarely better than 0.01 percent,

(ii) very limited ability to make logical decisions, store numerical data and provide extended time delays.

The points in favour of digital computers are,

(i) facility for memorizing numerical and non-numerical data indefinitely,

(ii) facility to perform logical operations and decisions,

(iii) accuracy does not depend much on the quality of the system components, but primarily depends on the number of bits contained in memory registers and by the specific numerical techniques selected for a particular problem.

The main drawback is that the computer time is relatively long and depends on the complexity of the problem (serial operation) involving the time sharing of all operationa

and memory units, only one or a limited number of operations being carried out at one time.

The Hybrid computer technique is an effort to combine in one computer system the advantages of both the analog and digital computers. The chief motivations behind hybridization are to combine the speed of the analog computers with the accuracy of the digital computers, to increase flexibility of analog simulation by using digital memory and logic capabilities, to increase digital computation speed by utilizing parallel analog subroutines and to handle data in systems which are partially continuous and partially discrete.

In a system of differential equations, if the frequency of solution of one variable is considerably different from the frequency of solution of the other variables, then it is very difficult to solve the equations efficiently with any numerical method. The same step size will not be suitable for all the variables. Pure analog simulation may also be difficult depending upon the complexity of terms. In such cases hybrid method can be effectively employed.

Hybrid computers are very effective for multivariable function generation. Hardware of costly non-linear elements are required to generate functions of two or more variables in an analog computer. Digital computers cannot be employed for generating continuous functions.

Hybrid computers are more efficient for solving partial differential equations compared to digital or analog computers.

Some of the major fields in which hybrid computation is being used are simulation of aircraft vehicles, missiles and space vehicles [9]. Hybrid simulation is used for the design and safety study of Nuclear power plants.

A hybrid computer system in its simplest form consists of an analog computer, a digital computer and an interface unit between the two. The interface should consist of a multiplexer, analog-to-digital converter (ADC), digital-to-analog converter (DAC) and a demultiplexer for communication between the two computers, a timing and control unit which synchronizes and controls the operation of the hybrid loop (the timing and control unit is mostly part of the digital computer). The block diagram of a hybrid computer system is shown in Fig. 1.1

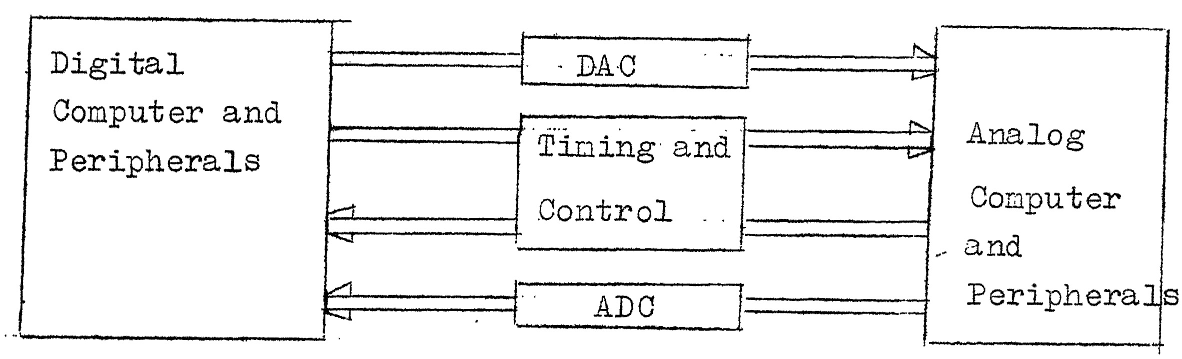


Fig. 1.1 Block diagram of a Hybrid Computer

1.2 HYBRID SYSTEM AT I.I.T. K.

For the hybrid system, the digital computer available was IBM 1800 (Data acquisition and control system) and the analog computer was AC 20 of ECIL make. A process computer should have the analog input - output terminals, process interrupt facilities, and interval timers IBM 1800 has these facilities and can be used as the digital part for a hybrid computer system.

The specifications of IBM 1800 and AC 20 are given in Appendix A.

Choudhary [3] and Sastry [14] of Electrical Engg. Department and Raghavan [10] of Computer Science programme have previously worked on the present facility.

1.3 OBJECTIVES

The main objective of the present work is to employ hybrid computer system for the simulation of thermal power plant, ~~simulation~~, specifically the 110 MW unit of Panki Thermal Power Plant. Since the hybrid system at I.I.T.K. is very small, large systems cannot be simulated on this. So, to start with, a small sub-system - the syperheaters of Panki Thermal Power Plant was selected for the present work since the number of dynamic equations are well within the limits of the present facility. A mathematical model of a Boiler unit is given in the IBM Report [5]. Sreenivasan [16]

developed a mathematical model for the Boiler unit of Panki Thermal Power Plant similar to this model. The mathematical model of the superheaters was selected for the present work. The model of the superheaters consists of seven differential equations only which are nonlinear and coupled in nature.

In the present work, the nonlinear model has been linearized around an operating point considering small perturbations. The hybrid simulation results for both linear and nonlinear models have also been compared.

One another objective is to find out how much accuracy the present system will give in simulating real systems. It is thus necessary to compare the hybrid simulation results with the actual results, here the pure digital simulation results using fourth order Runge-Kutta method.

De Boer and Dehes [4] simulated the steam generating system of a LMFBR with control loops in a hybrid computer system. They used applied Dynamics - 4/IBM 1800 hybrid computer facility at the Delft University of Technology for their work. The analog computer was used for the continuous integration and for the calculation of some of the parameters. Digital computer was used to calculate the coefficients used in the analog computer, to play back data from the previous time step to the analog computer, to calculate some of the parameters and to store data.

Paul Landaner [9] reported the simulation of the Pickering Nuclear Generating Station control to supplement the design work of individual loops and to review the performance of the plant control system before the plant went upto power.

1.4 TODAY'S HYBRID COMPUTER [13]

On sharp contrast to the relatively crude combinations of largely manually set analog computers alongwith second generation digital computers, today's hybrid computers are fully automatic, preprogrammed multiprocessors with problem set up accomplished in seconds and new parameters inserted and results obtained in micro or milliseconds. Thus systems are designed around advanced, hybridized analog and digital circuitry, together with software that can automatically provide the optimal combination of analog and digital solutions, operator-interactive high-level application of programming languages, and disk oriented foreground/background real-time operating systems. The average hybrid computer system has a speed equivalent to more than 100 million digital operations per second, giving a speed advantage of 20 to 150 times that for digital-only solutions for dynamic models.

CHAPTER 2

SUPERHEATER MODEL

2.1 INTRODUCTION

For the reasons mentioned in Chapter 1, the superheater part of the Boiler unit of the Panki Thermal Power Plant was taken for the present work. The boiler is a single drum, radiant, water tube, dry bottom circulation, coal fired boiler with superheaters and reheaters. Some important specifications of the boiler unit are given below [10].

Manufacturers : Bharat Heavy Electricals Ltd., India

Full Load Specifications :

Generating Capacity	110 MW
Steam flow rating	375 Tons/hr
Live Steam temperature (At final superheater outlet)	540°C
Pressure (At final superheater outlet)	139 Kg/cm^2
Drum Pressure	150 Kg/cm^2
Fuel	Pulverised coal
Calorific value of the fuel	32 percent by weight

The general layout and description of the plant is given in reference [10].

Steam is collected through the separators from the top position of the drum (Fig. 2.1). This steam at saturated conditions is led to ceiling superheater through headers. The steam coming out of the ceiling superheater is passed on in turn to convection superheater, platen superheater, and final superheater respectively. This superheated steam is supplied to steam turbines through throttle valves. The temperature of the superheated steam is controlled by attemperation at two places, i.e. between convection and platen superheaters and final superheater. The physical location of the various superheaters in relation to the furnace is as follows. Ceiling superheater comprises of the exposed surface of the furnace, platen superheater is situated at the top of the combustion chamber, and the final superheater at the exit of combustion chamber. Ceiling, platen and final superheaters receive heat mostly by radiation whereas convection superheater situated in the convection zone receives heat mostly by convection.

The superheaters are represented in three sections. The ceiling and convection superheaters are clubbed together and is termed as the primary superheater. The second section is assumed to be a unit which effectively simulates the flow dynamics of the superheater lines. This is imagined as a connecting link between primary and secondary superheaters. The secondary superheater consists of platen and

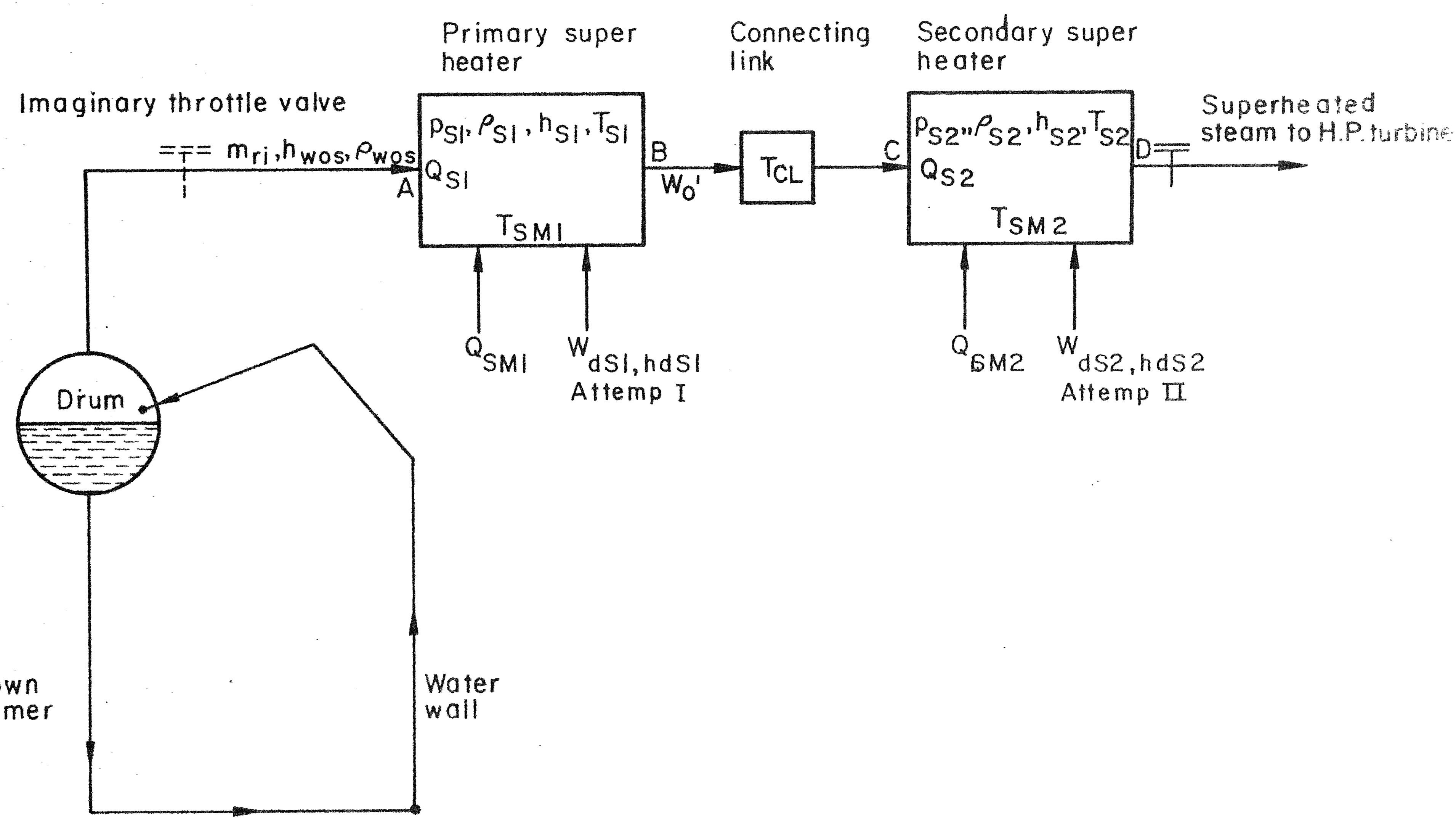


Fig 2.1 Model representation of superheater unit

final superheaters. It receives steam flow from the primary superheater through the linking line and discharges steam to the turbine through the throttle valves. The temperature of the superheated steam is controlled by attemperation carried out in primary and secondary superheaters.

2.2 PRIMARY SUPERHEATER

The mass and energy balance equations of primary superheater are given by [Section A to B of Fig. 2.1],

$$(m_{ri} - W'_o + W_{DS1}) = \frac{d}{dt}(V_{S1}\,\rho_{S1}) \tag{2.1}$$

$$\frac{dh_{s1}}{dt} = \left[\frac{dq_{s1}}{dt} + \frac{JP_{s1}}{\rho^2_{s1}}\frac{d\rho_{s1}}{dt}\right]\frac{1}{(1 - K_1 J)} \tag{2.2}$$

where

m_{ri} = evaporation rate or steam flow rate leaving the drum in kg/sec,

W'_o = mass flow rate of steam leaving the primary superheater in kg/sec,

ρ_{s1} = density of steam in the primary superheater in kg/m^3,

V_{s1} = volume of the primary superheater in m^3,

W_{DS1} = mass flow rate of attemperation spray added in kg/sec,

J = conversion factor (work to heat energy)

q_{s1} = net heat content in the primary superheater per kg of steam in kcal/kg and is given by

$$\frac{dq_{s1}}{dt} = [Q_{s1} + m_{ri}\, h_{wos} - W_o' h_1 + W_{DS1}\, h_{DS}] \frac{1}{\rho_{s1} V_{s1}} \qquad (2.3)$$

where

Q_{s1} = external heat added to the steam (primary superheater) in kcal/sec.,

h_{wos} = enthalpy of saturated steam entering primary superheater at drum pressure in kcal/kg,

h_{DS} = enthalpy of the attemperations spray in kcal/kg,

h_{s1} = enthalpy of steam in primary superheater in kcal/kg,

P_{s1} = pressure in the primary superheater in kg/m² and is given by,

$$P_{S1} = (K_1\, h_{S1} - K_2)\ \rho_{S1} \qquad (2.4)$$

where K_1 and K_2 are Callendar's proportional constants.

2.3 SECONDARY SUPERHEATER

The mass and energy balance equations of secondary superheater are given by [Section C to D of Fig. 2.1],

$$(W_o' - W_1 + W_{DS2})/V_{S2} = \frac{d}{dt}(\rho_{S2}) \qquad (2.5)$$

$$\frac{dh_{S2}}{dt} = [\frac{dq_{S2}}{dt} + \frac{JP_{S2}}{\rho_{S2}^2} \frac{d\,\rho_{S2}}{dt}] \frac{1}{(1 - K_1 J)} \qquad (2.6)$$

where

ρ_{S2} = density of steam in secondary superheater in kg/m^3,

W_{DS2} = mass flow rate of attemperation spray in kg/sec,

V_{S2} = volume of the secondary superheater in m^3,

W_1 = mass flow rate of steam going out of superheater through a throttle valve in kg/sec, and is calculated using the relation,

$$W_1 = CA \ (P_{s2} \rho_{s2})^{\frac{1}{2}} \tag{2.7}$$

where

C = throttle valve coefficient,

A = area of the throttle valve in m^2,

P_{s2} = pressure in the secondary superheater in kg/m^2 and is calculated using the relation,

$$P_{s2} = (K_1 \ h_{s2} - K_2) \rho_{s2} \tag{2.8}$$

where

h_{s2} = enthalpy of superheated steam in the secondary superheater in kcal/kg,

q_{s2} = net heat content in the secondary superheater in kcal/kg and is given by,

$$\frac{dq_{s2}}{dt} = [Q_{s2} + W_o' \ h_{s1} + W_{DS2} \ hd_s - W_1 h_{s2}] \frac{1}{\rho_{s1} V_{s1}} \tag{2.9}$$

where

Q_{s2} = external heat added to the steam in kcal/sec (secondary superheater).

2.4 CONNECTING LINK

This section (section B to C of Fig. 2.1) is assumed to be a unit effectively simulating the flow dynamics in the superheater lines. It can be thought of as a line connecting the primary and secondary superheaters which has no net heat loss or gain. The pressure drop across this unit determines the flow between the primary and secondary superheaters and this flow is modified by first order dynamics to incorporate an approximate representation of flow dynamics and is given by

$$T_{CL} \frac{dW'_o}{dt} = K_p \left(P_{s1} - P_{s2}\right) - W'_o \qquad (2.10)$$

where

T_{CL} = time delay constant for the connecting link in seconds,

K_p = a constant determined at the time of initialization

The time constant T_{CL} introduced will account for the dynamic lag in flow that would be experienced with changes in pressure and the transport delay that is associated with the superheater line lengths.

2.5 SUPERHEATER TUBES

The energy balance equations for the primary and

secondary superheater tubes are given by

$$(Q_{SM1} - Q_{s1})/C_{s1}\,M_1 = \frac{d}{dt}(T_{SM1}) \tag{2.11}$$

$$(Q_{SM2} - Q_{s2})/C_{s2}M_2 = \frac{d}{dt}(T_{SM2}) \tag{2.12}$$

where

C_{s1}, C_{s2} = Specific heat of primary and secondary superheater metal respectively, (kcal/kg$^\circ$C)

M_1, M_2 = Total weight of primarysupsuperheater metal, secondary superheater metal respectively, (kgs)

Q_{SM1}, Q_{SM2} = Heat transfer rate to primary and secondary superheater metal from gases respectively, (kcal/sec).

The rates of heat transfer from the tubes to the steam are calculated using empirical relations. Since the flow is turbulant, the relations used are

$$Q_{s1} = C_{ps}\,(W_o')^{nl}\,(T_{SM1} - T_{s1}) \tag{2.13}$$

$$Q_{s2} = C_{HS}\,(W_1)^{nl}\,(T_{SM2} - T_{s2}) \tag{2.14}$$

where

C_{ps}, C_{HS} = Coefficient of heat transfer from superheater metal to steam in primary and secondary superheater respectively,

n_1 = Turbulant heat transfer index,

T_{SM1}, T_{SM2} = Temperature of the primary and secondary superheater metal respectively, (^oC),

T_{s1}, T_{s2} = Temperature of steam in the primary and secondary superheater respectively, (^oC) and are calculated using the relations ,

$$T_{s1} = T_{H1}(h_{s1} - h_{sT1}) + T_{R1}(\rho_{s1} - \rho_{sT1}) + T_{sT1} \qquad (2.15)$$

$$T_{s2} = T_{H2}(h_{s2} - h_{sT2}) + T_{R2}(\rho_{s2} - \rho_{sT2}) + T_{sT2} \qquad (2.16)$$

T_{sT1}, T_{sT2} = Steady state operating temperature of steam in the primary and secondary superheater respectively.

$h_{sT1}, \rho_{sT1}, h_{sT2}$ and ρ_{sT2} represents the values $h_{s1}, \rho_{s1}, h_{s2}$ and ρ_{s2} respectively at steady state operating temperatures. Now, the differential equations can be rearranged with seven independent variables as follows :

$$\frac{d}{dt}(\rho_{s1}) = (m_{ri} - W_o' + W_{DS1})/V_{s1} \qquad (2.17)$$

$$\frac{d}{dt}(h_{s1}) = \left[\left[Q_{s1} + m_{ri}\, h_{wos} - W_o'\, h_{s1} + W_{Ds1}\, hds\right]\frac{1}{\rho_{s1} V_{s1}} + \frac{JP_{s1}}{\rho_{s_1}^2}\frac{d\rho_{s1}}{dt}\right]\frac{1}{(1 - K_1 J)} \qquad (2.18)$$

$$\frac{d}{dt}(\rho_{s2}) = \left[W_o' - W_1 + W_{DS2}\right]\frac{1}{V_{s2}} \qquad (2.19)$$

$$\frac{d}{dt}(h_{s2}) = \left[Qs2 + W_o' h_{s1} + W_{Ds2}\, h_{ds} - W_1\, h_{s2}\right]\frac{1}{\rho_{s2} V_{s2}} + \frac{JP_{s2}}{\rho_{s_2}^2}\frac{d}{dt}(\rho_{s2})\Big]\left(\frac{1}{1 - K_1 J}\right) \qquad (2.20)$$

$$\frac{d}{dt}(W_o') = \frac{K_p}{T_{CL}}(P_{s1} - P_{s2}) - \frac{W_o'}{T_{CL}} \tag{2.21}$$

$$\frac{d}{dt}(T_{sM1}) = (Q_{sM1} - Q_{s1})\frac{1}{C_{s1}M_1} \tag{2.22}$$

$$\frac{d}{dt}(T_{sM2}) = (Q_{sM2} - Q_{s2})\frac{1}{C_{s2}M_2} \tag{2.23}$$

2.6 LINEAR MODEL

2.6.1 Linearization [15]

In many investigations of nonlinear systems, a solution for a given set of initial conditions and excitation has been determined (either analytically or with the aid of a digital computer) and it is required to determine the behaviour of the system in the neighbourhood of this solution. For small perturbations from such a solution, the analysis reduces to that of a linear system.

Consider a nonlinear system with initial state $X(t_o)$ and input $U(t)$ in the form,

$$\dot{X} = f(X, U, t) \tag{2.24}$$

The solution of this equation is $X(t)$.

Let the initial condition is changed to $X(t_o) + x(t_o)$ and the input to $u(t) + U_1(t)$, where x and U_1 are both very small.

Since the resulting state will satisfy the differential equations, we can write

$$\dot{X} + \dot{x} = f(X + x,\ U + U_1,\ t) \tag{2.25}$$

Expanding the right hand side of (2.25) in Taylor's series,

$$\dot{X} + \dot{x} = f(X,U,t) + \frac{\partial f}{\partial X}\, x + \frac{\partial f}{\partial U}\, U_1 + \text{higher - order terms} \tag{2.26}$$

$$\text{(i.e.)}\ \dot{x} = \frac{\partial f}{\partial X}\, x + \frac{\partial f}{\partial U}\, U_1 + \text{higher - order terms} \tag{2.27}$$

If the higher-order terms are small, they may be neglected in obtaining an approximate solution to the problem and the resulting perturbation equation is seen to be linear.

2.6.2 Linear Model

Using the above method, all the non-linear equations are linearized in the present work. The state and input vectors are as follows :

$$\underline{X}^T = [\,\rho_{s1}\ h_{s1}\ \rho_{s2}\ h_{s2}\ W_o'\ T_{sM1}\ T_{sM2}\,] \tag{2.28}$$

$$\underline{U}^T = [A\ W_{DS1}\ W_{DS2}] \tag{2.29}$$

As an example, the linearization of eqn. (2.19) is given below.

$$\frac{d}{dt}(W_o') = \frac{K_p}{T_{CL}}(P_{s1} - P_{s2}) - \frac{W_o'}{T_{CL}}$$

where

$$P_{s1} = (K_1\ h_{s1} - K_2)\ \rho_{s1}$$

$$P_{s2} = (K_1\ h_{s2} - K_2)\ \rho_{s2}$$

After substitution eqn. (2.19) can be written as

$$\frac{dX_5}{dt} = \frac{K_p}{T_{CL}} [(K_1\ X_2 - K_2)\ X_1 - (K_1\ X_4 - K_2)X_3] - \frac{X_5}{T_{CL}} \qquad (2.30)$$

Linearizing,

$$\frac{dx_5}{dt} = \frac{K_p}{T_{CL}} [K_1\ x_2\ X_{10} + (K_1\ X_{20} - K_2)\ x_1 -$$
$$[K_1\ x_4\ X_{30} + (K_1\ X_{40} - K_2)\ x_3]] - \frac{x_5}{T_{CL}} \qquad (2.31)$$

where X_{10}, X_{20} and X_{30} represent the steady-state values of X_1, X_2 and X_3 respectively.

This can be written in the form,

$$\dot{x}_5 = A(5,1)\ x_1 + A(5,2)\ x_2 + A(5,3)\ x_3 + A(5,4)\ x_4 +$$
$$A(5,5)\ x_5 + A(5,6)x_6 + A(5,7)\ x_7 + B(5,1)\ U_1(1)$$
$$+ B(5,2)\ U_1(2) + B(5,3)\ U_1(3) \qquad (2.32)$$

where the coefficients are given by

$$A(5,1) = \frac{K_p}{T_{CL}} (K_1\ X_{20} - K_2)$$

$$A(5,2) = \frac{K_p}{T_{CL}} (K_1\ X_{10})$$

$$A(5,3) = -\frac{K_p}{T_{CL}} (K_1 X_{40} - K_2)$$

$$A(5,4) = -\frac{K_p}{T_{CL}} (K_1 X_{30})$$

$$A(5,5) = -1/T_{CL}$$

$$A(5,6) = 0$$

$$A(5,7) = 0$$

$$B(5,1) = B(5,2) = B(5,3) = 0$$

Similarly all the equations are linearized and the model obtained is in the form,

$$\dot{\underline{X}} = [A]\ \underline{X} + [B]\ \underline{U}$$

The operating point taken for the linearization are given below.

$$\underline{U}^T = [A \quad W_{DS1} \quad W_{DS2}] = [0.3041 \quad 4.444 \quad 3.472]$$

$$\dot{\underline{X}} = \begin{bmatrix} \rho_{S1} \\ h_{S_1} \\ \rho_{S2} \\ h_{S2} \\ W'_o \\ T_{SM1} \\ T_{SM2} \end{bmatrix} = \begin{bmatrix} 77.4327 \\ 663.786 \\ 40.1474 \\ 819.112 \\ 107.334 \\ 380.099 \\ 568.09 \end{bmatrix}$$

The matrix A and matrix B obtained after linearization are shown below :

$$[A] = \begin{bmatrix} 0.0 & 0.0 & 0.0 & 0.0 & -.0256 & 0.0 & 0.0 \\ -.177 & -.183 & 0.0 & 0.0 & -.284 & 0.128 & 0.0 \\ 0.0 & 0.0 & -.238 & -.0135 & 0.086 & 0.0 & 0.0 \\ 0.0 & 0.298 & -8.21 & -3.651 & 2.0 & 0.0 & 1.709 \\ .726 & 0.284 & -1.296 & -.148 & -.039 & 0.0 & 0.0 \\ 0.011 & 0.0085 & 0.0 & 0.0 & -.0012 & -.0079 & 0.0 \\ 0.0 & 0.0 & 0.0132 & .029 & 0.0 & 0.0 & -.0168 \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0.0 & 0.0256 & 0.0 \\ 0.0 & 0.125 & 0.0 \\ -31.41 & 0.0 & 0.086 \\ -775.8 & 0.0 & 0.9099 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ -1.318 & 0.0 & 0.0 \end{bmatrix}$$

CHAPTER 3

SOFTWARE AND SET UP FOR HYBRID COMPUTATION

3.1 INTRODUCTION

Since an overall idea about the IBM 1800 TSX system is necessary for the understanding of the software used, it will be discussed briefly first. Although Raghavan [10] in his work had developed the software required for the hybrid system, a new set of subroutines are developed in this case. This was necessary because one of the main tasks was to reduce the digital computer time as far as possible. A lot of variables and subroutines used in Raghavan's software package were unnecessary for the present problem.

3.2 IBM 1800 TSX SYSTEM

Time Sharing Executive (TSX) and Multiprogramming Executive (MPX) are supervisory programs supplied by IBM to operate IBM 1800 computer. MPX is an improved and sophisticated version of TSX. Since to use MPX efficiently the computer should have at least 24K memory, the IBM 1800 at I.I.T.K. uses TSX. TSX is a FORTRAN oriented disk - resident operating system which permits the user to make optimum use of an IBM 1800 Data Acquisition and Control System (DACS) for its primary purpose, the control of processes and similar environments, as well as providing the user with an effective

off-line monitor system for data processing and scientific computation.

A 'process program' is one that continuously monitors a control process. A process program uses process subroutines through which the process input - output devices are operated like digital and analog input - output devices, interrupt device, clocks etc. For the hybrid computation, the process capabilities of IBM 1800 are used to give analog signals, to read analog inputs and to control the modes of the analog computer. Process programs are classified into three :

i) Interrupt Program

This is a process program which can be executed by creating an interrupt. An interrupt can be created by one of the following methods a) pressing the 'KBD REQ' key of the I/O typewriters, b) closing of a process interrupt contact point (these points are displayed on a panel on the back-side of the IBM 1800).

ii) Mainline (Queue) Program

This is a process program which is executed by queuing it. A mainline program can be placed in the queue by any process program.

iii) Combination Program

This is a process program which can be executed either by queuing it or by creating an interrupt.

3.3 MODE CONTROL OF ANALOG COMPUTER

In a hybrid set up the three main modes of the analog computer, RESET, COMPUTE and HOLD are to be controlled by the digital computer. Three subroutines written serve this purpose. This is actually attained by using the digital output - ECO (Electronic Contact Operate) points. The relay positions of integrators for mode control [1] and the circuit designed by Choudhary [3] to attain it using the IBM 1800 are given in Appendix B.

3.4 ANALOG READ - WRITE

Two subroutines (other than the system subroutines) are necessary for analog read and analog write because of the disparities in voltages between analog and digital computers. The analog computer voltage varies from -10 V to + 10 V. The analog output voltage of the digital computer ranges from 0 to +10 V for the output points 00 and 01. Remaining output points give output in the range 0 to + 5 Volts. The analog input to the digital computer can vary from -5 V to +5V (This is when solid state multiplexer is used. For relay multiplexer it is 0 to $\pm$ 5 volts; only one sign is applicable at a time). Level shifting circuits are necessary to compensate these disparities. The circuits used are shown in Fig. 3.1.

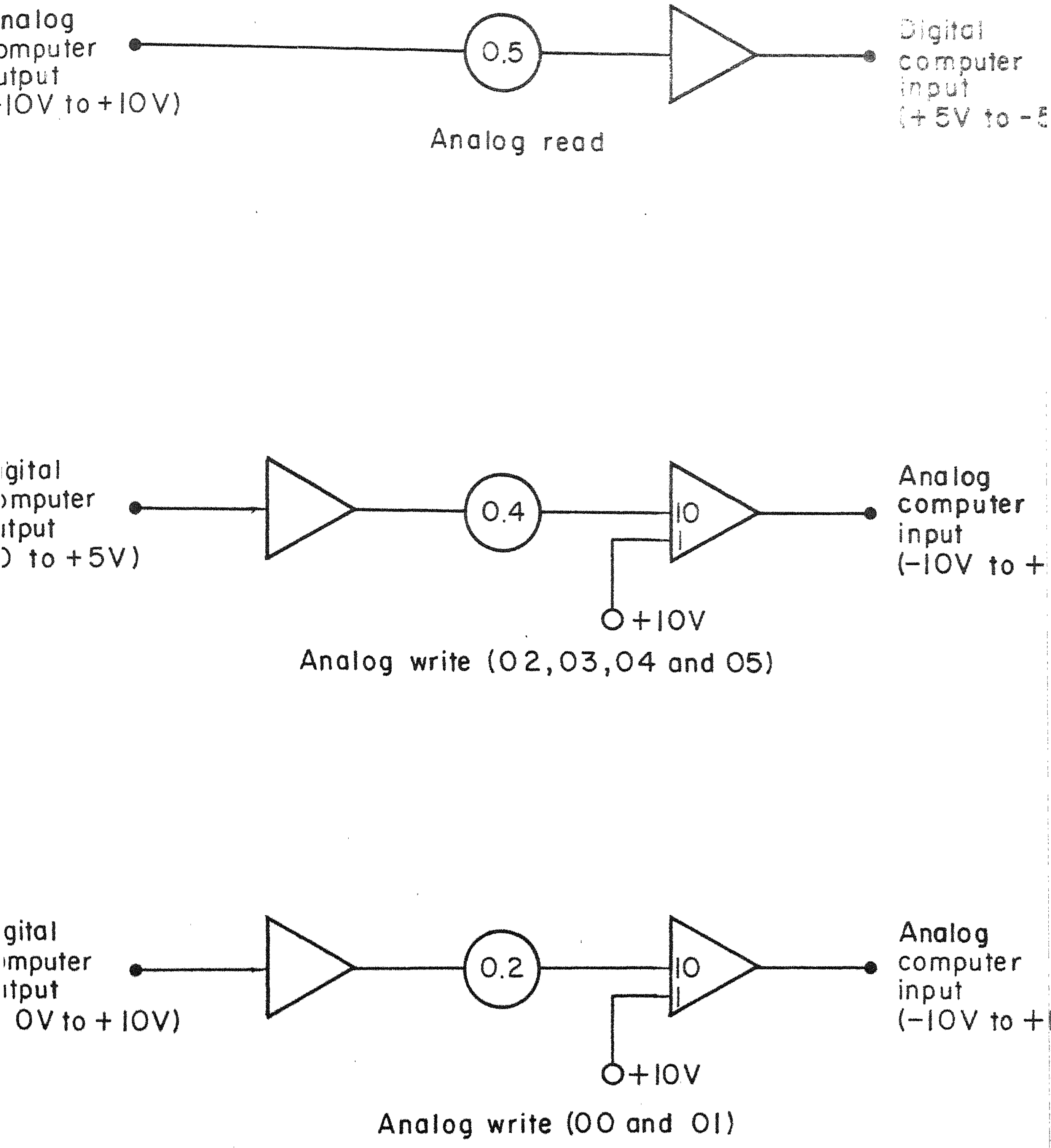


Fig. 3.1 Analog read-write interface level shifting circuits

3.5 HYBRID ROUTINES

Program RAGVN

This is an interrupt coreload program. When the interrupt button on the interface unit is depressed, this routine will be transferred to core and executed. This program queues BALGO.

Program BALGO

This puts the analog computer in reset mode and initialises all output voltages to zero. This queues the hybrid program 'HYBR'.

Program RAGS

This is a mainline coreload program. This is a dummy routine and is necessary to delete HYBR. (HYBR is called in BALGO and it can not be deleted unless its call in BALGO is substituted by another mainline coreload program name. RAGS serves this purpose).

Subroutine RESET

This puts the analog computer in reset mode.

Subroutine COMPT

This puts the analog computer in compute mode. A timer is called in this routine immediately after the analog computer is put in compute mode. The calling statement of this routine is CALL COMPT (TYM). 'TYM' specifies the compute

time of the hybrid system in seconds. The routine 'TIME' will be called after every 25 seconds and a variable is equated to 1, the value of which was initially zero, when the compute time elapses. So, to check whether the compute is over or not, the value of this variable is checked in the hybrid program frequently. If this value is 1, the analog computer will be put in reset mode, otherwise, the computation will be continued.

Subroutine RDAI

This reads sequentially 7 analog input points to the digital computer and converts them to the corresponding analog voltages starting from the address point K and puts the values in the array X(1) to X(7). The calling statement is CALL RDAI (X,K).

Subroutine WRAO

This first makes the voltage 'VALUE' to be written in the digital computer output range and then writes the value at the particular address point 'JPT'. The calling statement is CALL WRAO (VALUE, JPT).

Subroutine TIME

This routine is called every 25 seconds. When the compute time is over, the variable 'BALU' in this routine is equated to 1.

Subroutine TIMEF

This is to fool the compiler of IBM 1800 because it does not permit the name of a subroutine within itself. Routine 'TIME' is to be called every 25 seconds and this is not possible within 'TIME' itself. So TIMEF is called in TIME and this calls TIME every 25 seconds.

Subroutine SST

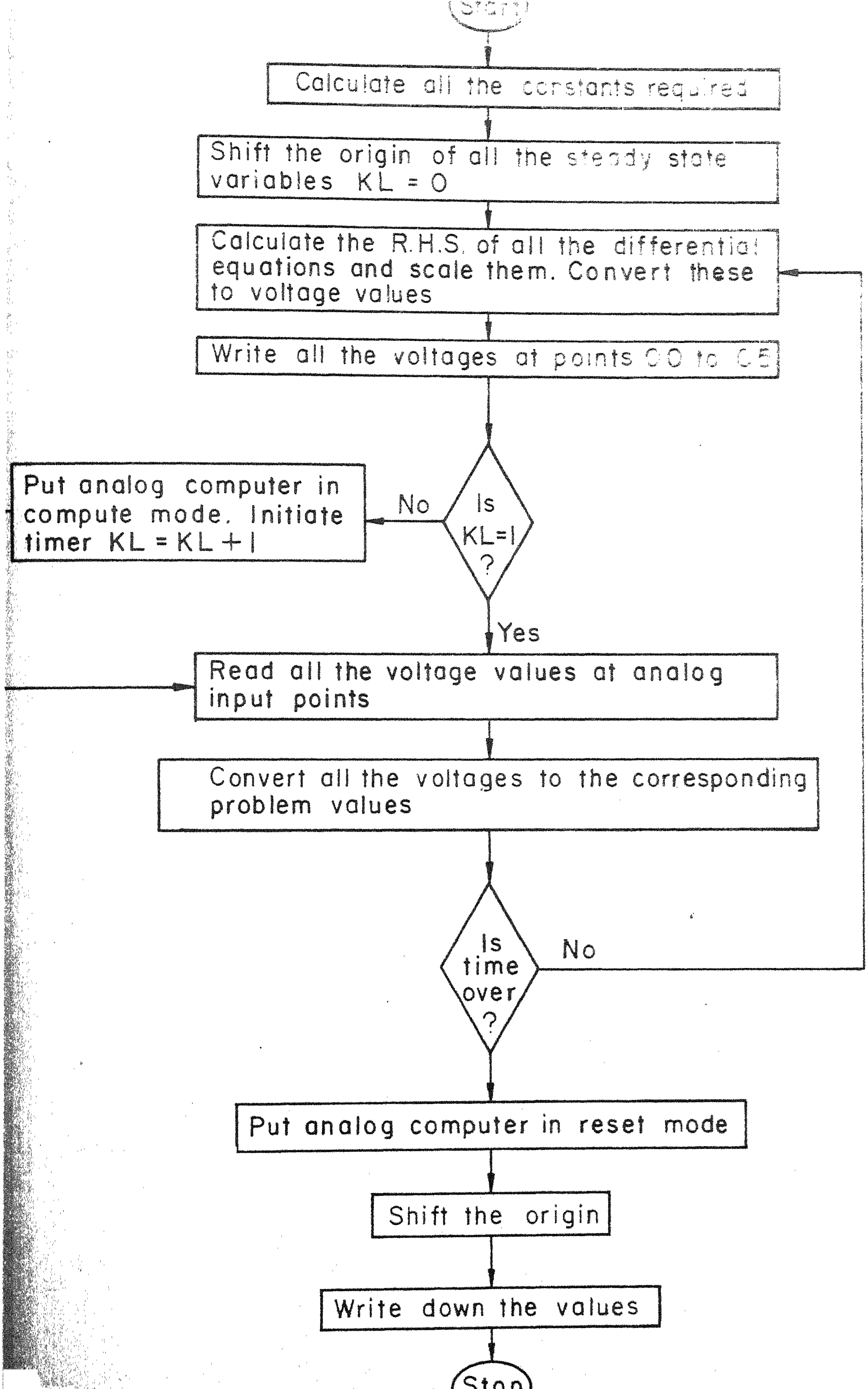
This subroutine is called in 'HYBR' frequently to check whether the compute time is over or not.

3.6 SEQUENCE OF EXECUTION

When the interrupt button on the interface unit is depressed, RAGVN will be executed. This queues BALGO. When a program is queued the programs existing before the beginning of the execution of the queued program are overwritten in memory and this program is executed whereas a called program always forms part of a coreload. BALGO queues the hybrid program 'HYBR'. The flow chart of the hybrid program is given in Fig. 3.2.

3.7 PROBLEM PATCH-UP ON HYBRID SYSTEM

Out of the seven differential equations, the first one (eqn. 2.17) is solved completely on the analog computer.


Start
Calculate all the constants required
Shift the origin of all the steady state variables KL = O
Calculate the R.H.S. of all the differential equations and scale them. Convert these to voltage values
Write all the voltages at points OO to O5
Is KL=1 ?
No
Put analog computer in compute mode. Initiate timer KL = KL + 1
Yes
Read all the voltage values at analog input points
Convert all the voltages to the corresponding problem values
Is time over ?
No
Put analog computer in reset mode
Shift the origin
Write down the values
Stop

The operational amplifiers and potentiometers of AC 20 are used for the problem patch-up. The potentiometers and operational amplifiers of TR 20 are used for the level shifting circuits. In general, the analog part is used for the continuous integration and for the level shifting circuits. The digital port controls the modes of the computer, reads the analog voltages, calculates the algebraic equations and gives back the signals to the analog computer and stores the intermediate values. The complete set up is shown in Fig. 3.3.

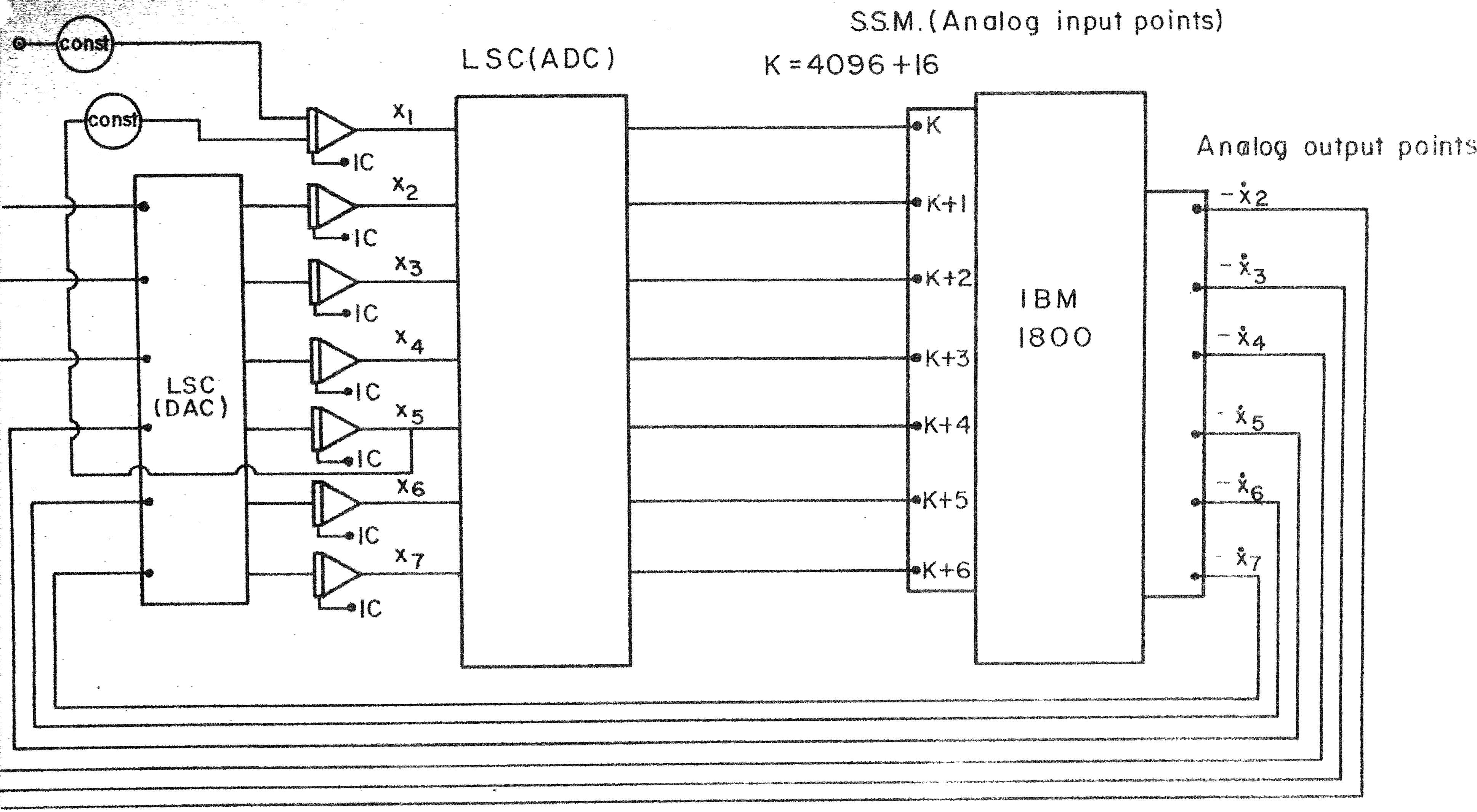
3.8 SCALING THE EQUATIONS

3.8.1 Time Scaling

Time scaling is used in analog computers to slow down or speed up the solution. The idea is that the maximum frequency of oscillation of the solution of a differential equation should be within the bandwidth of the analog computer components.

In hybrid computers time scaling is used to slow down the analog computer so as to have the required number of samplings in one cycle of the highest frequency variable.

One of the most serious errors in hybrid system is the time-delay error. This is the effect of digital execution time in a hybrid computer. The analog to digital conversion of the voltages, its processing and converting back to analog



LSC-Level shifting circuit
SSM-Solid state multiplexer

Fig. 3.3 Problem patch up

voltages will take a finite amount of time. During this time the analog computer would have continued to compute. So, if the amount of computation on the digital computer is increased in order to raise accuracy, execution time is prolonged and so, increased computing error may result. According to Truitt [18], as a good rule of thumb, a sampling rate of about 50 to 100 per cycle of the highest frequency variable will keep the time-delay error within 0.1 percent. From the linear model of the present system, it can be seen that the frequency of the highest frequency variable is .... 3.65 rad/sec. (i.e.) 0.581 cycles/sec. In the real time simulation the data were transferred 120 times in 50 seconds, that is 2.4 times in a second. This shows that in real time simulation, the time-delay error will be considerable for this system. The analog computer was slowed down using $t = \tau/6$ for the nonlinear model and $t = \tau/4.5$ for the linear model [11].

3.7.2 Amplitude Scaling

The purposes of amplitude scaling are, i) the amplifiers should not get overloaded, ii) the full dynamic range, namely $\pm V_{ref}$ (the range over which the amplifiers are designed to work - reference voltage) of all amplifiers should be utilized.

In the present work, to utilize the full range of all the operational amplifiers, the origin of the state variables

was shifted to a new value. This is done by using

$$\underline{Z} = \underline{X} - \underline{G} \tag{3.1}$$

where $\underline{Z}$ represents the new state after shifting the original state $\underline{X}$ to the origin $\underline{G}$. All the equations were reformulated using this scheme. The values of the origin $\underline{G}$ for various percentage openings of the throttle valve area are given in Table 3.1.

After shifting the origin the equations were amplitude scaled using the normalised variable technique [11].

A listing of the subroutines and programs used for the present hybrid simulation is given in Appendix C.

Table 3.1

	10 percent increase in throttle valve area non-linear model	20 percent increase in throttle valve area non-linear model	10 percent decrease in throttle valve area non-linear model	10 percent increase in throttle valve area linear model
ρ_{s1}	73.4327	69.4327	81.4327	-4
h_{s1}	659.786	655.789	667.786	-4
ρ_{s2}	38.1474	36.1474	42.1474	-2
h_{s2}	811.112	803.112	827.112	-8
W'_o	110.334	113.334	104.334	+3
T_{SM1}	378.0099	376.0099	382.0099	-2
T_{SM2}	563.09	558.09	663.09	-5

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS OF HYBRID AND DIGITAL SIMULATION

Hybrid simulation of a thermal power plant sub-system has been done in this work. The sub-system consists of the primary and secondary superheaters and their linking component. The highly nonlinear mathematical model has been linearized around a normal operating point of the plant. Simulation is done with both the non-linear and linear model.

The digital simulation results were obtained using the 4th order Runge-Kutta method. In hybrid simulation, the analog computer was slowed down using $t = \tau/6$ for the non-linear model. So, for 50 seconds of plant operation, the time taken in hybrid simulation is 300 seconds or 5 minutes. It is to be noted that the digital simulation using Runge-Kutta method took two hours on IBM 1800 to get 50 seconds of plant response (It took only 6 minutes on IBM 7044).

Using the time scale $t = \tau/6$ data were transferred 722 times between analog and digital computer within 50 seconds of real time (the plant operation time), that is, a sampling rate of 14.4 times/sec. or 24.6 times/cycle of the maximum frequency variable. This sampling rate is sufficiently high and the time delay errors can be ignored.

In the linear model, since the complexity of terms in the digital computer were less, a higher sampling rate was used. We obtained a sampling rate of 14.16 times/sec. with $t = \tau/4.5$. That is the hybrid simulation of linear model took only 225 seconds for the 50 seconds plant response. This clearly shows that if we can reduce the calculations done in digital computer, the solution time can also be reduced considerably.

The responses obtained for the various perturbations were satisfactory. A step increase in throttle valve area (Figs. 4.1, 4.2 and 4.4) means an increase in steam flow-rate, w_O'. For the constant attemperation sprays, the step increase in throttle valve area reduces the densities ρ_{S1} and ρ_{S2}. Similarly since the heat input is constant, the enthalpies h_{S1} and h_{S2} and temperatures T_{SM1} and T_{SM2} decrease. All these stabilise around a new operating point after some time.

Similarly a reduction in throttle valve area, with the other inputs as constants reduces the steam flow w_O' and increases all the parameters, ρ_{S1}, h_{S1}, ρ_{S2}, h_{S2}, T_{SM1} and T_{SM2} (Fig. 4.3).

The maximum error between the results obtained from hybrid simulation and that from the digital simulation is seen to be only of the order of 1 percent (Figs. 4.1 to 4.4).

4.2 LIMITATIONS OF THE PRESENT HYBRID FACILITY AND SUGGESTIONS FOR FURTHER WORK

In the present hybrid facility only a maximum of ten integrators are available for use. Large system models having more than ten differential equations cannot be simulated in this set-up. If the analog computer capacity can be increased, larger systems can be simulated. Presently only one AC 20 and three TR 20 are available and the AC 20 is coupled to IBM 1800. If one TR 20 is coupled to the IBM 1800 the other two TR 20 can be slaved along with this so that a maximum of 24 integrators will be available for simulation.

One other limitation is that the operational amplifiers of the analog computer are subject to drifts if operated for a longer time. In simulating larger systems, the digital computation time is increased but the same sampling rate is to be maintained to avoid time-delay errors. In order to match the increased digital execution time, the analog computer has to be slowed down by time-scaling. Thus the analog computer will have to be in compute mode for a longer time interval where by the results may be affected due to the drifts as mentioned earlier.

The IBM 1800 at I.I.T.K. can give only 6 analog outputs. For simulating larger systems we need more than six analog outputs.

If we can use separate digital-to-analog converter in conjunction with IBM 1800, the digital output terminals can be used to give analog signals thereby enhancing the number of analog outputs.

During the simulation of larger systems, digital or analog compensating techniques [17] can be used to reduce the time-delay errors. No such compensating method was used in the present study because a suitable choice of time - scaling was possible and which gave satisfactory results.

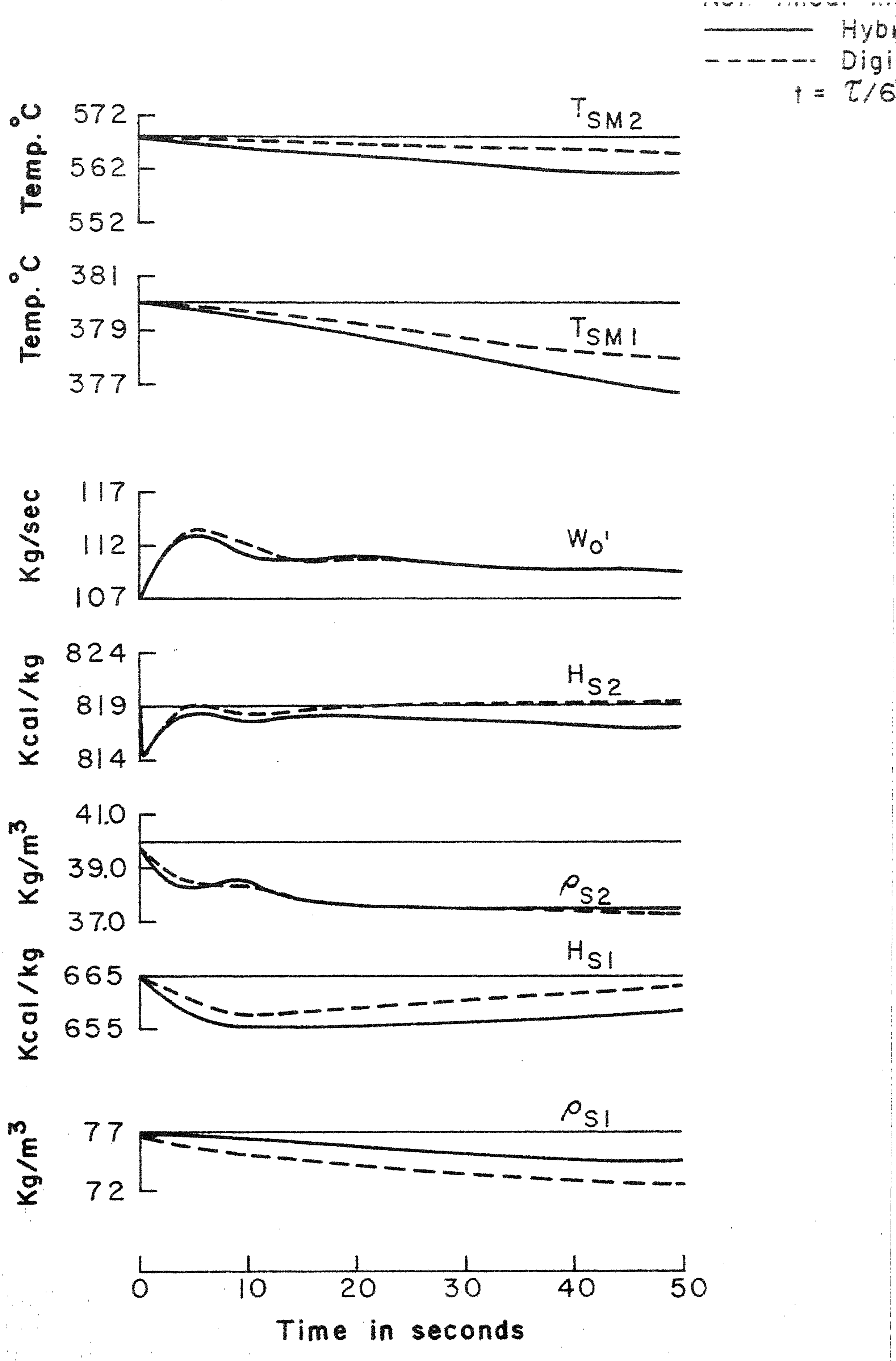


Fig. 4.1 10% step increase in throttle area

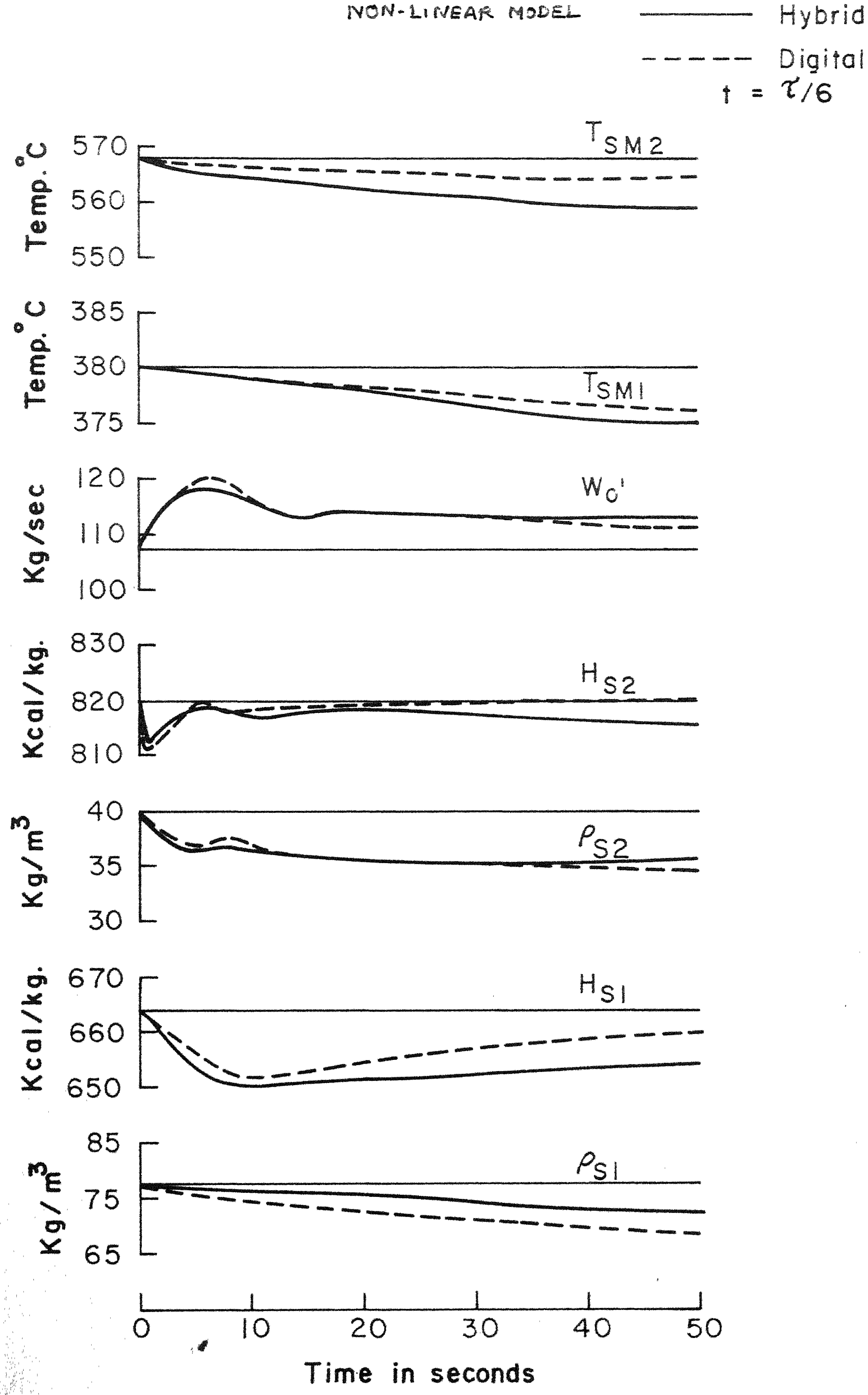
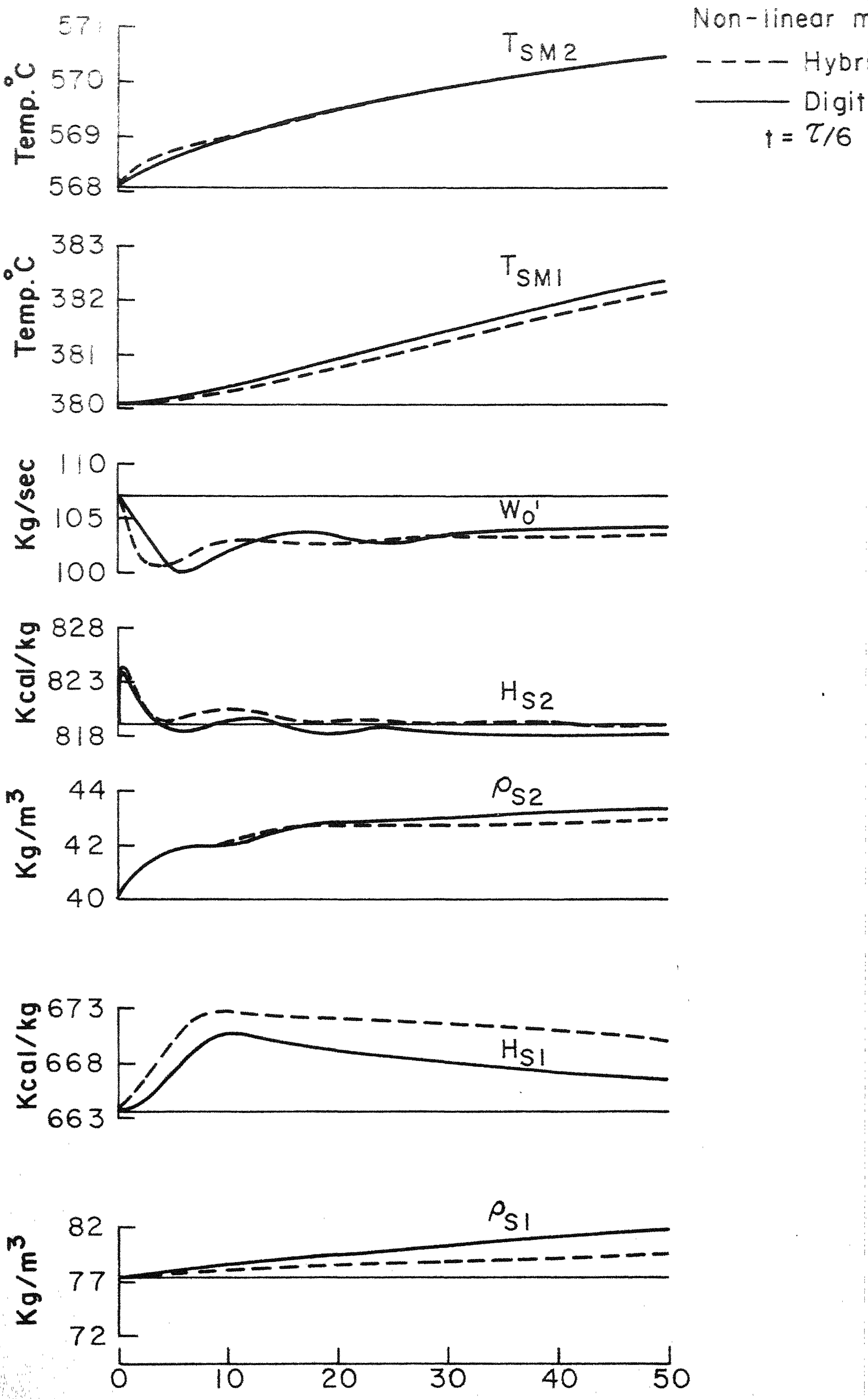
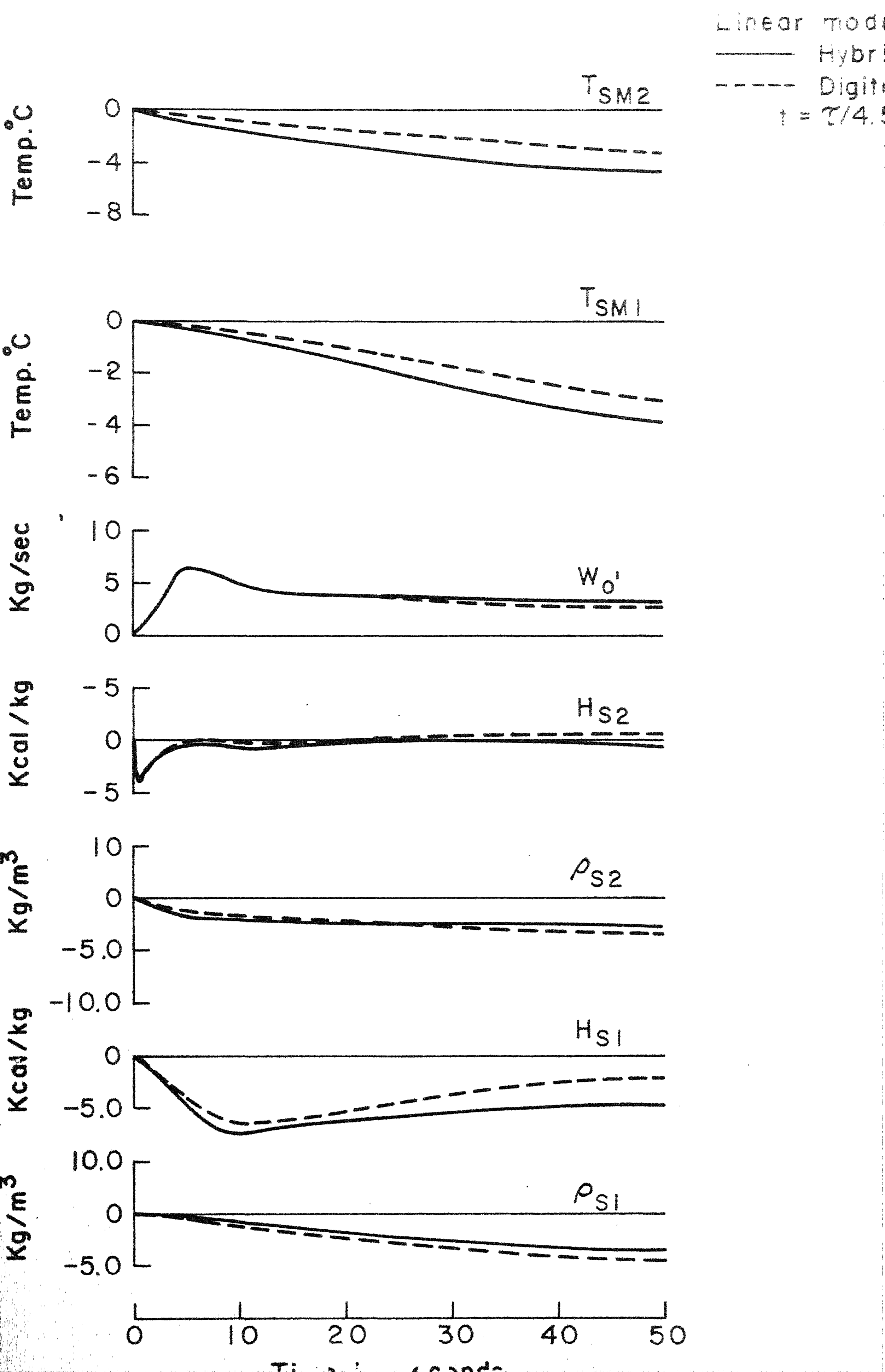


Fig 4.2 20% step increase in throttle area



Non-linear m
Hybr
Digit
t = τ/6
Temp. °C
57
570
569
568
T_{SM2}
Temp. °C
383
382
381
380
T_{SM1}
Kg/sec
110
105
100
W_0'
Kcal/kg
828
823
818
H_{S2}
Kg/m³
44
42
40
ρ_{S2}
Kcal/kg
673
668
663
H_{S1}
Kg/m³
82
77
72
ρ_{S1}
0
10
20
30
40
50



Temp. °C
T_{SM2}
Temp. °C
T_{SM1}
Kg/sec
W_0'
Kcal/kg
H_{S2}
Kg/m³
ρ_{S2}
Kcal/kg
H_{S1}
Kg/m³
ρ_{S1}
0 10 20 30 40 50

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APPENDIX A

A-1 IBM 1800 Specifications [6]

1. Word Length : 18 bits (16 data bits, 1 bit for parity check, 1 bit for storage protection)
2. Main Memory : 16 K words (expandable to 64K words)
3. Memory Cycle Time : 4 µsec.
4. Instruction execution times : 9 µsec. for addition, 30 µsec. for multiplication, 85 µsec. for division etc. for integer arithmetic.
5. Analog Input
   i) Solid State Multiplexer - Switching rate is 10,000 points per sec. 64 analog inputs can be connected. Permissible voltage range is from -5V to +5V.
   ii) Relay Multiplexer - Switching rate is 100 points/sec. 15 analog inputs can be connected. Permissible voltage range is from-.5 to +5 V.
6. Digital input

   12 sets (16 bits each) of digital input terminals. Out of these 12 sets, two sets are of contact sense type and the rest are of voltage sense type.
7. Analog output

   Six analog output terminal points (addresses from 00 to 05) 00 and 01 give voltages from 0 to + 10V and the remaining from 0 to + 5V.

8. Digital output

12 sets (16 bits each) of digital output terminals. Two sets are of electronic contact operate (ECO) type and the rest are of voltage sense type.

9. Process interrupt switches : 3 sets of 16 bits each of contact sense type.

10. Interval Timers : Three interval timers, A,B and C. Timer A and B are wired for .25 ms and 1 ms time bases respectively. Timer C acts as a real time clock.

A-2 AC 20 Specifications [1]

This is an ECIL make analog computer.

1. Total 20 operational amplifiers ($\pm$ 10V) with five inputs (3 of unity gain and two with a gain of 10). All of them can be used as summers/inverters while 10 of them can be used as integrators also.
2. 4 Quarter square multipliers ($\pm$ 10 V)
3. One universal diode function generator ($\pm$ 10V).
4. 30 ten turn hand - set helical potentiometers.

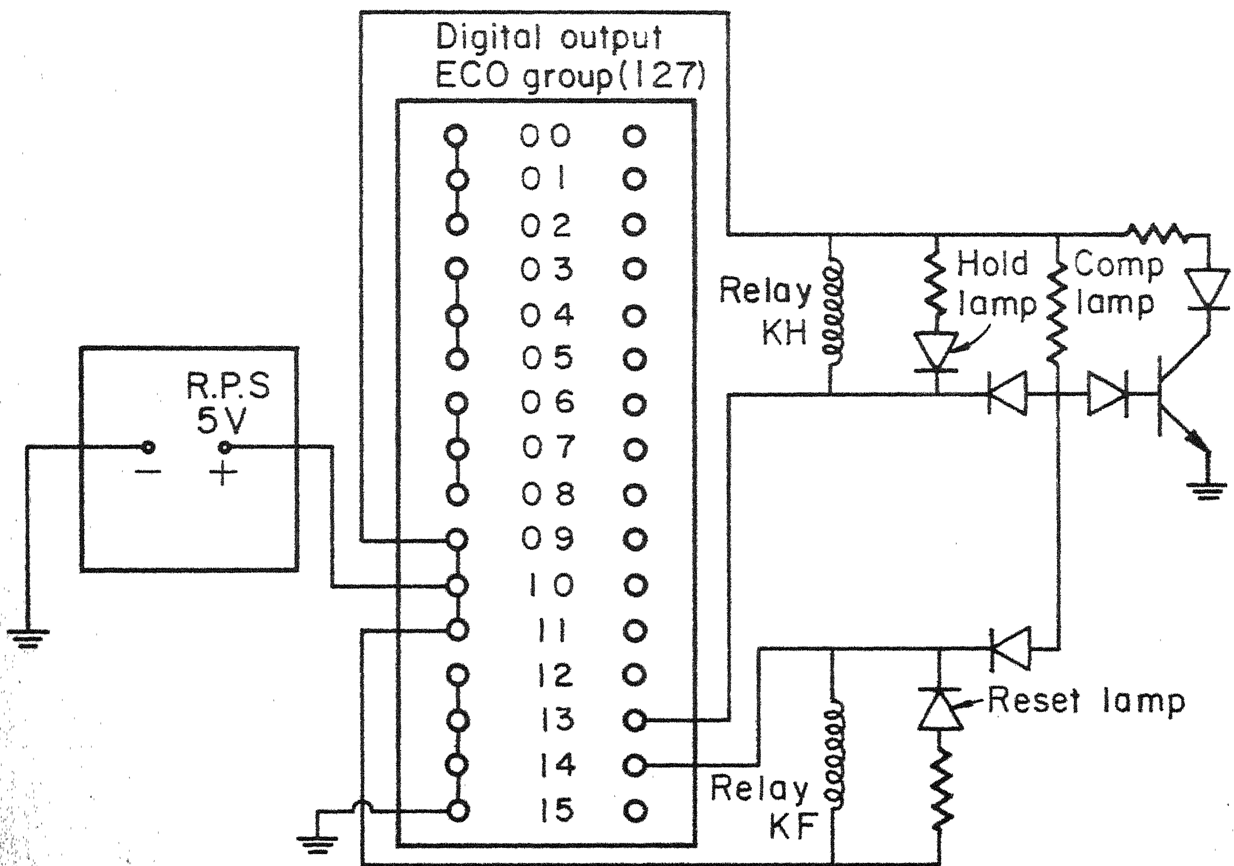
Appendix B

Mode	KF	KH
Reset	I	I
Compute	O	O
Hold	O	I

I – Relay energised

O – Relay denergised

Relay positions for mode control



Mode control circuit

APPENDIX C

HYBRID ROUTINES

```
// JOB
// DUP
// FOR RAGVN
C  ** THIS IS THE HYBRD INTERRUPT RESPONSE ROUTINE
      EXTERNAL BALGO
      CALL QUEUE(BALGO,1,0)
      CALL ENDTS
      CALL INTEX
      END
*STORECI  I            RAGVN RAGVN RAGVN 0505
*CCEND


// JOB
// DUP
*SEQCH BALGO HYBR,RAGVN
*DELETE   M            BALGO
// FOR BALGO
*IOCS(TYPEWRITER)
      EXTERNAL HYBR
C  ** THIS QUEUES HYBRD PROGRAM
      DIMENSION L(3)
      DATA L/6,127,2/
      CALL CO(11001,L(1),L(3))
      PAUSE
      CALL QUEUE(HYBR,1,0)
      DO 11 I=1,6
11    CALL WRAO(0.0,I-1)
      CALL VIAQ
      END
*STORECI  M            BALGO BALGO BALGO
*CCEND
*SEQCH HYBR BALGO,RAGVN


// JOB
// DUP
*SEQCH RAGS HYBR,BALGO RAGVN
*DELETE   M            RAGS
// FOR RAGS
*IOCS(TYPEWRITER)
C  ** THIS IS A DUMMY PROGRAM
      WRITE(1,15)
15    FORMAT(#WISH YOU ALL THE BEST#)
      CALL VIAQ
      END
```

```
*STORECI  M             RAGS  RAGS  RAGS
*CCEND
*SFQCH HYBR RAGS,RAGSJ RAGVA


// JOB
// DUP
*DELETE                 RDAI
// FOR RDAI
      SUBROUTINE RDAI(X,K)
      DIMENSION IDATA(9),X(7)
C   **  THIS SUBROUTINE READS 7 ANALOG INPUTS SERIALLY
C   **  FROM THE ADDRESS K ONWARDS AND STORES IN X
      IDATA(9)=8
      CALL AIS(01001,IDATA(1),IDATA(9),K)
1     CALL AIS(0,ITEST)
      GO TO (1,2),ITEST
2     KN=0
      DO 10MN=1,7
      KT=7-KN
      X(KT)=IDATA(MN)
10    KN=KN+1
      DO 15 MN=1,7
15    X(MN)=-X(MN)/1638.4
      RETURN
      END
*STORE                  RDAI
*CCEND


// JOB
// DUP
*DELETE                 WRAO
// FOR WRAO
      SUBROUTINE WRAO(VALUE,JPT)
C   **  THIS SUBROUTINE PLACES A VOLTAGE#VALUE#AT THE
C   **  ANALOG OUTPUT POINT#JPT#.
      DIMENSION JDATA(3)
      JDATA(3)=2
      JDATA(2)=JPT
      IF(JPT-6) 5,10,10
C   ** 6553.6/4=1638.4(INTERFACE DISPARITY)
5     JDATA(1)=1638.4*(VALUE+10.)
      CALL DAC(11001,JDATA(1),JDATA(3))
1     CALL DAC(0,JTEST)
      GO TO (1,2),JTEST
2     RETURN
10    WRITE(1,15)
15    FORMAT(#WRAO ADDRESS WRONG#)
      RETURN
      END
*STORE                  WRAO
*CCEND
```

```
// JOB
// DUP
*DELETE                 COMPT
// FOR COMPT
      SUBROUTINE COMPT(TYM)
C   **  THIS SUBROUTINE PUTS THE ANALOG COMPUTER IN
C   **  COMPUTE MODE AND INITIATES THE TIMER.TYM
C   **  SPECIFIES THE COMPUTE TIME IN SECONDS
      EXTERNAL TIME
      DIMENSION L(3)
      COMMON BALU,KP,KS
      DATA L/0,127,2/
      KP=0
      JCONT=TYM
      KS=JCONT/25
      BALU=0.0
      CALL CO(11001,L(1),L(3))
      CALL TIMER(TIME,2,25000)
      RETURN
      END
*STORE                  COMPT
*CCEND


// JOB
// DUP
*DELETE                 RESET
// FOR RESET
      SUBROUTINE RESET
      DIMENSION JDATA(3)
C   **  THIS SUBROUTINE PUTS THE ANALOG COMPUTER
C   **  IN RESET MODE
      DATA JDATA(1),JDATA(2),JDATA(3)/6,127,2/
      CALL CO(11001,JDATA(1),JDATA(3))
      RETURN
      END
*STORE                  RESET
*CCEND


// JOB
// DUP
*DELETE                 SST
// FOR SST
      SUBROUTINE SST(JTST)
      COMMON BALU,KP,KS
C   ** JTST WILL BE 1 IF COMPUTE TIME IS OVER
      JTST=BALU
      RETURN
      END
*STORE                  SST
*CCEND
```

```
// JOB
// DUP
*DELETE                 TIME
// FOR TIME
      SUBROUTINE TIME
      COMMON BALL,KP,KS
C   **  THIS ROUTINE IS ENTERED AFTER EVERY 15 SECONDS
C   **  BALL IS SET TO 1 WHEN COMPUTE TIME IS OVER
      KP=KP+1
      IF(KP-KS) 10,12,12
10    CALL TIMEF
      RETURN
12    BALL=1
      RETURN
      END
*STORE                  TIME
*CCEND


// JOB
// DUP
*DELETE                 TIMEF
// FOR TIMEF
      SUBROUTINE TIMEF
C   **  THIS IS TO PUT THE ANALOG COMPUTER IN COMPUTE
C   **  MODE FOR MORE THAN 32 SECONDS.
      EXTERNAL TIME
      CALL TIMER(TIME,2,25LCC)
      RETURN
      END
*STORE                  TIMEF
*CCEND


// JOB
// DUP
// FOR IDLE
      SUBROUTINE IDLE(TIM)
C   ** THIS ROUTINE IS INTENDED TO PROVIDE ANY DELAY REQUIRED AT ANY
C   ** DELAYS AREREQUIRED,FOR EXAMPLE,AFTER A MODE CHANGE COMMAND TO
C   ** COMPUTE SINCE NO COMPUTATIONS SHOULD BE DONE UNTIL ANALOG HASC
C   ** MODE AND IT TAKES ABOUT 100MSEC FOR MECH CONTACTS TO CLOSE
C   ** THE LOOP BELOW IS A 8.5MS LOOP
      N=TIM/.0085
      DO1I=1,N
      QZ=1.0/1.*2./2./1./3./3.
1     CONTINUE
      RETURN
      END
*DELETE                 IDLE
*STORE                  IDLE
*CCEND
```

THIS IS THE HYBRID PROGRAM

```
// JOB
// DUP
*STORE HYBR RAGS,BALGC
*DELETE    M            HYBR
// FOR HYBR
*IOCS(TYPEWRITER,KEYBOARD)
      REAL MR1,K1,K2,J,N1,KP,M1,M2
      DIMENSION X(?),X1(85),X2(85),X3(85),X4(85),X5(85),X6(85),X7(85
      MR1=102.5
      PI=3.1416
      VS1=PI/4.*((0.0523**2)*32.*113.+(0.0397**2)*112.*226.)
      VS2=PI/4.*((0.0326**2)*18.*215.+(.035**2)*12.*235.
     1+(0.0355**2)*26.*224.)
      K1=96.5
      K2=45000.
      HWCS=626.7
      HDS=247.64
      J=0.00235
      N1=0.8
      C=0.0891*SQRT(0.3048)
      CPS=6000./(107.334**0.8*20.)
      HST1=664.5955
      ROST1=76.5111
      TST1=360.
      TH1=1.073033
      TR1=1.384795
      TH2=1.76
      TR2=1.3795
      HST2=820.
      ROST2=40.2576
      TST2=540.
      KP=108.5/110000.
      DAV=0.0392
      VEL=3750.*0.02004/(9.*PI*DAV**2*224.)
      TCL=200./VEL
      CS1=0.164
      CS2=0.164
      M1=PI*0.0523*2.*0.008*32.*113.*8020.
     1+PI*0.04*2.*0.0045*112.*226.*8020.
      M2=PI*0.04*2.*0.045*0.1*30.*440.*8020.+PI*0.0392*2.*0.009*26.
     1*224.*8020.
      CHS=18660.0/(112.2**0.8*30.)
      QSM1=6000.
      QSM2=18660.
      ROS1=77.4327
      HS1=663.786
      HS2=819.112
      ROS2=40.1474
      WO1=107.334
      TSM1=380.099
      TSM2=568.09
      A1=0.3041
      A=A1
```

```
      WDS1=160./36.
      WDS2=125./36.
      X(1)=ROS1
      X(2)=HS1
      X(3)=ROS2
      X(4)=HS2
      X(5)=WO1
      X(6)=TSM1
      X(7)=TSM2
      KL=0
      WRITE(1,5)
5     FORMAT(#WRITE DOWN STEP CHANGE VALUES OF THREE INPUTS IN F3.1#
      READ(2,8) Z11,Z12,Z13
8     FORMAT(3(F3.1))
      A=Z11*A1
      WDS1=Z12*WDS1
      WDS2=Z13*WDS2
      KBG=0
      I=1
      G1=71.4327
      G2=655.786
      G3=36.1474
      G4=803.112
      G5=113.334
      G6=376.099
      G7=558.09
      H1=0.6
      H2=0.8
      H3=0.4
      H4=2.0
      H5=1.0
      H6=0.4
      H7=1.0
      X(1)=X(1)-G1
      X(2)=X(2)-G2
      X(3)=X(3)-G3
      X(4)=X(4)-G4
      X(5)=X(5)-G5
      X(6)=X(6)-G6
      X(7)=X(7)-G7
10    KBG=KBG+1
      X(1)=X(1)+G1
      X(2)=X(2)+G2
      X(3)=X(3)+G3
      X(4)=X(4)+G4
      X(5)=X(5)+G5
      X(6)=X(6)+G6
      X(7)=X(7)+G7
      X1(I)=(MR1-X(5)+WDS1)/VS1
      PS1=(K1*X(2)-K2)*X(1)
      TS1=TH1*(X(2)-HST1)+TR1*(X(1)-ROST1)+TST1
      QS1=CPS*X(5)**N1*(X(6)-TS1)
      F11=(QS1+MR1*HWGS-X(5)*X(2)+WDS1*HDS)/(X(1)*VS1)
      X2(I)=(F11+J*PS1*6.*X1(I)/(X(1)*X(1)))/(1.0-K1*J)
      PS2=(K1*X(4)-K2)*X(3)
```

```
      W1=C*A*(PS2*X(5))**0.5
      X3(I)=(X(5)-W1*US2)/VS2
      TS2=TH2*(X(4)-ST2)+TH2*(X(3)-RTST2)+TST2
      QS2=CHS*W1**N1*(X(7)-TS2)
      F33=(QS2+X(5)*X(2)-WTS2*HIS-W1*X(4))/(X(3)*VS2)
      X4(I)=(F33+J*PS2*6.*X3(I)/(X(3)*X(3)))/(1.0-K1*J
      X5(I)=KP/TCL*(PS1-PS2)-X(5)/TCL
      X6(I)=(QSM1-QS1)/(QS1*M1)
      X7(I)=(QSM2-QS2)/(QS2*M2)
      X(2)=-X2(I)/H2
      X(3)=-X3(I)/H3
      X(4)=-X4(I)/H4
      X(5)=-X5(I)/H5
      X(6)=-X6(I)/H6
      X(7)=-X7(I)/H7
      DO 1011 KAL=2,7
1011  X(KAL)=X(KAL)/6.0
      JPT=0
      DO 40 K=1,6
      KR=K+1
      VALUE=X(KR)
      CALL WRAC(VALUE,JPT)
40      JPT=JPT+1
      IF(KL) 21,21,25
21    CALL COMPT(300.)
      KL=KL+1
      CALL IDLE(3.0)
      KN=4112
25    CALL RDAI(X,KN)
      X(1)=X(1)*H1
      X(2)=X(2)*H2
      X(3)=X(3)*H3
      X(4)=X(4)*H4
      X(5)=X(5)*H5
      X(6)=X(6)*H6
      X(7)=X(7)*H7
      X1(I)=X(1)
      X2(I)=X(2)
      X3(I)=X(3)
      X4(I)=X(4)
      X5(I)=X(5)
      X6(I)=X(6)
      X7(I)=X(7)
      IF(KBG-KBG/10*10) 12,13,12
13    I=I+1
12    CALL SST(JTST)
      IF(I-100) 26,28,28
26    IF(JTST) 10,10,28
28    CALL RESET
      DO 60 KS=1,I
      X1(KS)=X1(KS)+G1
      X2(KS)=X2(KS)+G2
      X3(KS)=X3(KS)+G3
      X4(KS)=X4(KS)+G4
      X5(KS)=X5(KS)+G5
```

```
      X6(KS)=X6(KS)+36
.0    X7(KS)=X7(KS)+9,
      WRITE(1,101) 
.01   FORMAT(I4)
      DO 35 KO=1,I
      WRITE(1,100) X1(KO),X2(KO),X3(KO),X4(KO),X5(KO),X6(KO),X7(KO)
100   FORMAT(4(2X,E15.8))
35    CONTINUE
      CALL VIAQ
      END
*STORECI  M          HYBR  HYBR  HYBR
*CCEND
*SEGCH RAGS HYBR,BALGO
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